Design and Fabrication of Solar-Electric Hybrid Space Heating System

By

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Approval Sheet

Certified that the contents and form of the thesis entitled "Design and Fabrication of Solar-Electric Hybrid Space Heating System" submitted by Ms. Mominah Ahmad, Ms. Mehwish Akhtar, and Mr. Saad-ul-Khaf have been found satisfactory for the requirement of the degree of Bachelors of Environmental Engineering.

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Abstract

The energy demand worldwide is increasing parallel to the excessive rise in world's population. Significant part of the residential sector energy demand worldwide is consumed for space heating purposes. Typical heating methods employing biomass or fossil fuels emit indoor air pollutants causing significant health and environmental impacts. To cater for increased global energy demand and reduction of indoor air emissions, clean yet affordable and efficient sources of energy need to be used which Sustainable Development Goal no. 7 aims at. Solar Energy in Pakistan and surroundings has got the potential to be employed as a fuel for many household applications. Hybridized solar thermal and electric power systems provide sustainable solutions aiming at health protection, environmental preservation and energy optimization. The objective of this project is to fabricate a sustainable and energy efficient space heating system that provides thermal comfort to household inhabitants and ensures acceptable indoor air quality. The project also aimed at fabricating the system by using locally available materials to optimize the costs. The system designed is made to run on two fuels: Solar energy or electrical energy. The system comprises of indoor as well as outdoor units. Radiator, hybridization tank, solar collector dish and solar radiation receiver are main units with control systems installed in between for process regulation. During sufficient solar radiation availability, water present in receiver is heated when the dish concentrates solar radiation onto it. This water is pumped to flow through the radiator present indoor. When solar radiation reaching Earth is hindered, water is heated through electric water heater immersed in hybridization tank. System testing was conducted in Islamabad during winter season. The testing phase involves water heating through both of the fuels to check for individual method's efficiency as well as adequacy of the radiator design. Based on the results obtained through experimentation and analysis of past data, it is analyzed that solar radiation available during the day and being intercepted by designed outdoor system (efficiency: 74%) is sufficient to provide enough heat to maintain room's temperature in thermal comfort range based on ASHRAE Standards. Also, the hybridized system single-handedly provides enough power to heat up the room, all through the day with thermal efficiency of 44%. The system can be coupled with water heating and automated through the use of thermostatic valves as well as solar tracking to reduce labor-intensive loads and to increase efficiency.

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1 Introduction

1.1 Background

It is estimated that at present more than 7 billion people are breathing in this world and this number continues to rise at a distressing rate. The subsequent rise in energy demand and the fact that most of it is being fulfilled today by fossil fuel combustion, cannot be ignored. The Sustainable Development Goal no. 7 demands provision and access of clean, affordable, reliable and modern energy for all. The highest energy demand in residential and institutional buildings globally is for space heating and air conditioning depending upon geographical location. *(Illikainen, K., & Sirviö, 2015).* Conventional employment of fossil fuel and biomass combustion heaters to heat spaces indoors has undesirable impacts on health of inhabitants as well as environment. Moreover the use of sub-standard and insecure methods of heating spaces is highly energy intensive making operational and maintenance costs sky-high. Typical pollutants given off during combustion of fossil fuels indoors include CO_2, CO, NO_x, SO_x and particulate matter (PM) of both primary and secondary types.

According to *WHO Guidelines, 2017*, an estimated 4.3 million people die prematurely every year, with an absolute no. of deaths in range of 50,000-500,000 people in Pakistan in year 2016 (Figure 1.1). The low income countries are more vulnerable to health impacts of indoor air pollution. The extent of exposure in terms of the number of people, exposure intensity and time spent exposed is far greater in the developing world *(Smith, 1993)*. Approximately 76% of all global particulate matter air pollution occurs indoors in the developing world. The rate and frequency of upsurge of chronic diseases related to respiratory, nervous and immune system is also very high. Extensive dependence on fossil fuels is causing natural resources to deplete massively on a global scale. Large scale deforestation needs a mention here as around 70% of Pakistani households depend on fuel wood for energy *(Hamayun, Khan, & Khan, 2013)*. Consequently, the land surface and soil become more vulnerable to erosion. The indoor air pollutants contribute to about 6% of global greenhouse gas emissions, with CO_2 being the dominant GHG contributor. The release of NO_x, CO and VOCs in high amounts is resulting in increased rate of tropospheric ozone formation.

The use of fossil-fuel generated electricity is limited due to high capital and operational costs and questionable availability over space. To eliminate the enormous list of problems associated with conventional heating methods, there is a dire need to explore sustainable heating methods and renewable sources of energy.

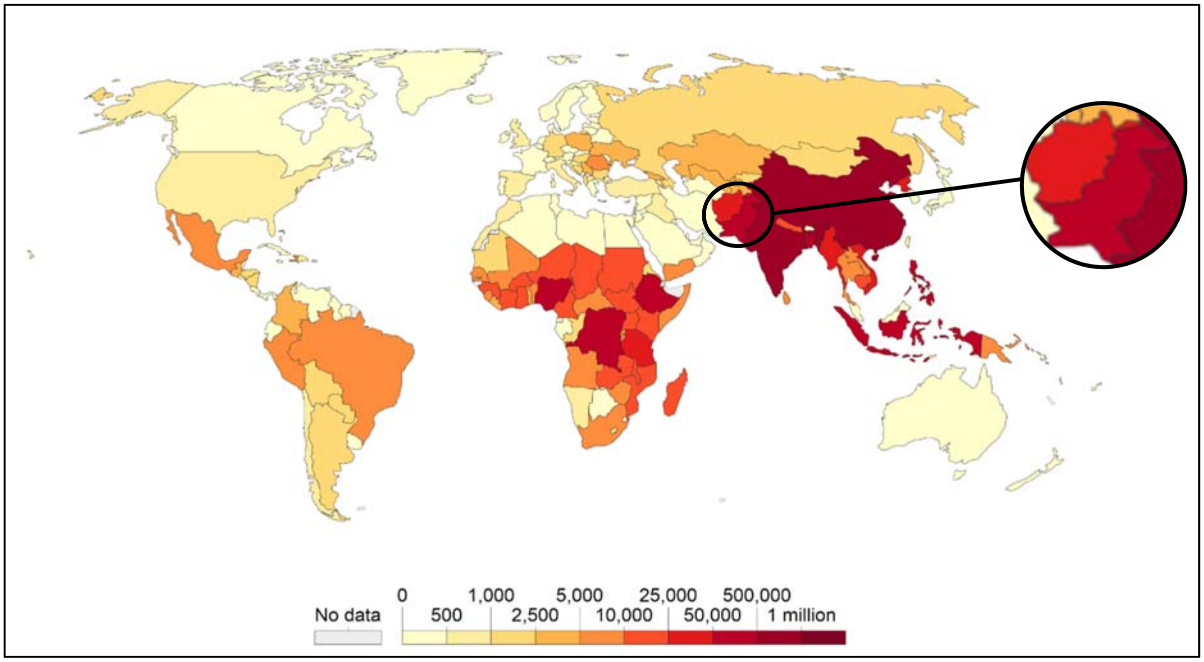

Figure 1.1 Annual number of premature deaths as a result of household air pollution from the use of unclean fuels for cooking and space heating

Solar Thermal energy is one of the two types through which solar energy can be harvested and used. Thermal applications are drawing increasing attention in the solar energy research field, due to their high performance in energy storage density and energy conversion efficiency *(Y. Tian, 2013).* The thermal energy output of Sun is 2.8×10^{23} kW. The Earth is able to receive limited amount of solar radiations as per its cross section in the path of radiations. The amount reaching Earth's surface is further reduced due to losses radiations face while travelling in outer space. Irradiation is an amount of solar energy received on a unit surface expressed in units of kWh/m^2. The irradiation and insolation are variable both over time and space *(B.H. Khan, 2006).* Keeping in view the geographical location of Pakistan, the solar energy can effectively be employed for various applications in residential as well as industrial sectors. Pakistan lies immediately above tropic of cancer, receiving huge amount of solar energy throughout the year. The average solar radiation incident on Islamabad has intensity value ranging from 4.5-5kWh/m^2/day throughout the year with value of 4-4.5kWh/m^2/day specific for winter months i.e. from November to February (*NREL, 2007*).

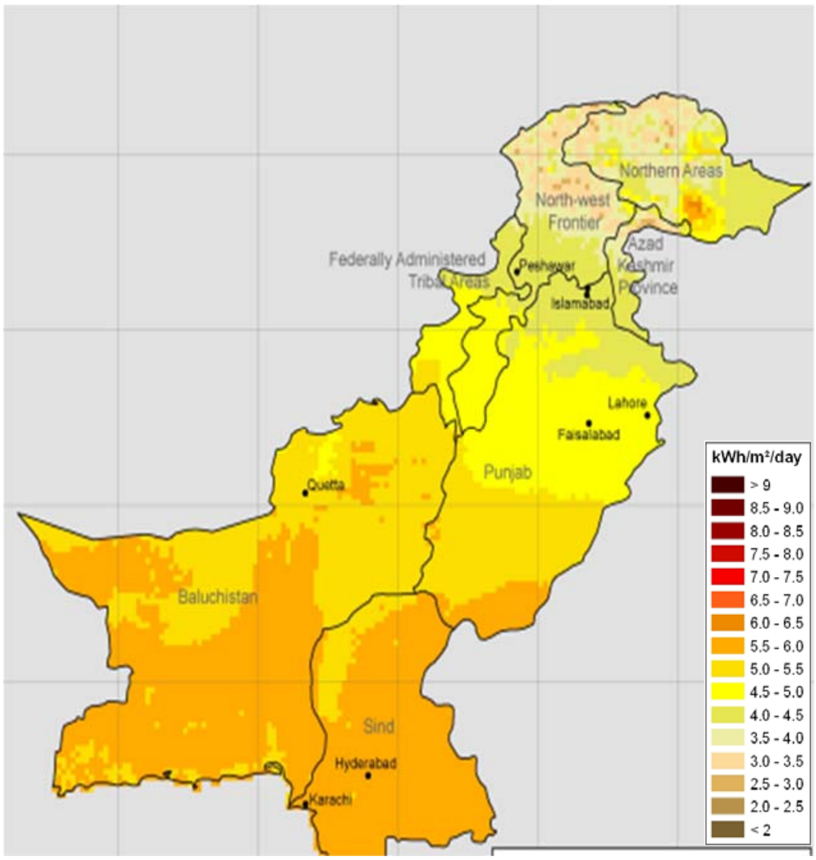

Figure 1.2 Spatial Variation of solar radiation intensity during winters in Pakistan

Solar thermal energy is the use of solar energy in direct form rather than converting it into electricity first, which is the case with Photovoltaics. The abundant direct solar radiation availability harvesting through mechanisms and strategies that involve low capital cost, zero operational costs as well as minimal pollutant emissions proves the reliability of solar thermal energy as a fuel for multiple applications in different sectors as well as provides an area of interest in which more research can be carried out to make it more effective and adaptable in different sectors and at all levels. The use of solar energy in either form is limited through its restricted availability over time.

To enhance the reliability of systems to acceptable limits, it is almost essential to hybridize renewable energy sources with more persistent energy source. Because air pollutant emissions are extremely low indoors when using on-grid electricity, it is preferred over other fuels that employ combustion indoors. Thus, solar thermal systems hybridized with electrical energy provide an efficient and reliable method for smooth and sustained operations of systems while making optimal energy use and reducing operational costs.

1.2 Problem Statement

Traditionally fossil-fuel, biomass and electric powered heaters are being used to achieve acceptable levels of thermal comfort in residential and institutional buildings which operate at high energy costs and have adverse impacts on health and environment.

1.3 Research Objectives

To present a sustainable solution for aforementioned problem, two objectives are being intended. The first one is to design a fully functional Solar-Electric Hybrid Space heating system that is energy efficient, cost-saving and has very low negative impacts on indoor air quality. The second objective aims at employing locally available materials to optimize high capital costs associated with typical heating methods in use, worldwide.

1.4 Scope

The project is based on design of a durable and efficient space heating system that is fueled by two energy sources, in order to never compromise on uninterrupted functioning of the system under different conditions. The system is designed to be used in residential and institutional buildings where a big percentage of energy requirement during winters is due to space heating.

The primary fuel for the process is solar thermal energy, which is clean, reliable and abundant source of energy. For effective capture of solar energy, solar concentrating dish is used. A parabolic dish was used with self-applied reflective material to save costs of pre-fabricated solar dishes. During the course of project, the dish was being supported on a manually adjustable stand but it can be automated easily for highly precise and less labor-intensive solar tracking. For hybridized system that employs electrical energy as the secondary fuel, the heating element in use is a low cost AC-run electric rod. Initially it was intended to use a DC-run electric rod but during experimentation phase and time-heating rate optimization, it was found unsuitable. Though no damage was observed in our case, if properly installed and insulated the safety concerns accompanying use of AC electric rod are eliminated. The rod is being thermostatically controlled to save energy and associated costs. Locally available copper pipes and tubes are used in radiator manufacture and the design is kept so as to maximize heat transfer rate, the effectiveness of which was proved after test results were analyzed. The indoor and outdoor systems were tested for their energy input and output as stand-alone systems. However, the integration of outdoor system with radiator itself couldn't be done due to time restraints. The analysis though, was performed after the results were obtained that related energy requirements with that available.

Initially, market research of different radiators was done and their energy budgeting was performed to allow understanding of possibilities of energy saving or optimization in different areas of the system. Keeping in view the research, the system is designed so as to achieve maximum output out of the energy input. It is kept as simple as possible with margin of flexibility given if any alterations need to be done. Significant saving in energy expenses is observed if the proposed prototype is compared to its market competitors and/or if run solely on solar thermal energy.

2 Literature Review

2.1 Typical Emission Factors for common household space heaters

Most common indoor air pollutants given off during household fossil fuel or biomass based cook stoves or heaters include Carbon dioxide, Carbon monoxide, Particulate matter, Nitrogen oxides, Sulphur oxides and Methane. These emissions directly affect nervous and respiratory system functions. The atmospheric transport of primary emissions up to considerable length and chemical conversion of some of the precursors into secondary pollutant, constitutes some of the indirect impacts of these emissions. The following table presents average specific emission rate of some of most common pollutants from various fuels enlisted in order of their usage from low to high income countries. The heaters used in estimation are traditional unvented type. *(Rufus Edwards, 2014)*

Table 2.1 Emission factor of common household fuels for space heating

Sr. No	Fuel	Emission Factor (g/kg)			
		CO	**CO_2**	**CH_4**	**PM_{10}**
1	Dung cake	42.9	1000.5	11.63	2.45
2	Wood	52.8	1610	8.9	2.5
3	Charcoal	162.3	2559	6.2	3.2
4	Crop Residue	68.7	2005	6.2	3.2
5	Natural Gas	21	3440	0.014	0.016

Source: World Health Organization, 2014

2.2 Material Selection

2.2.1 Heat Transmission Material

Initially, extensive research was conducted to select heat transmission medium for the heat exchanger i.e. radiator. The heat transfer medium used in radiators should have maximum thermal conductivity, high resistance to corrosion under variable temperature ranges and should be cost effective. Different metals and alloys are compared based on different parameters like thermal conductivity, corrosion-resistance, cost and local availability.

Table 2.2 List of different heat transmission materials and their properties

Sr. No	Material	Thermal Conductivity (W/m.K)	Resistance to Corrosion	Cost	Local Availability
1	Copper	385.0	Low	Competitive	Yes
2	Steel	50.2	Low	Low	Yes
3	Aluminum	205.0	Low	High	Variable
4	Cast Iron	79.5	High	Low	Yes
5	Titanium	544.3	High	High	No
6	Brass	109.0	Low	Competitive	Variable

Based on in-depth analysis, copper is chosen as heat transfer medium because of its highly favorable characteristics.

2.2.2 Working Fluid

In a thermodynamic system, the working fluid is a liquid or gas that absorbs or transmits energy and does work on the system. In radiators, working fluid or Heat Transfer Fluid (HTF) may either be water, steam or organic fluid carrying heat that it transfers to transmission media which in return transmits the heat to air. The favorable properties needed for efficient heat transfer from HTF to transmission material include fluid's low viscosity, high thermal stability, less toxicity to minimize safety and maintenance concerns and to fulfill our research objectives specifically, it should be locally available.

Table 2.3 List of Heat Transfer Fluids and their properties

Sr. No	Fluid	Thermal Stability	Viscosity	Toxicity	Local Availability
1	Distilled water	High	Low	Low	Yes
2	Dielectric oil	Low	High	Moderate	Yes
3	Nanofluids	High	Variable	Moderate	No

The working fluid to be used in this project is water based on properties that favor scope of this project.

2.2.3 Thermal Insulator

Thermal insulators are materials used to reduce heat losses from a system. For this project's requirement they must be used to minimize convective and radiative losses from receiver and connecting pipes. Different insulators are compared against their working temperature ranges, R-value that measures resistance to heat flow and eco-supportive nature.

Table 2.4 Comparison between different locally available thermal insulators

Sr. No	Material	Low Temperature Range (°C)	High Temperature Range (°C)	R-Value Per inch (K. m²/W)	Cost	Eco-Friendly
1	Fiberglass	-30	540	3.1	Moderate	Yes
2	Mineral Wool (glass)	0	250	3.1	Moderate	Yes
3	Rock wool	0	760	3.1	Low	Yes
4	Polyurethane Foam	-73	121	6.3	Moderate	No
5	Polystyrene	-50	80	4	Low	No
6	Cellular Glass	-260	480	4.7	High	Yes

Out of these, rock wool is selected because of favorable properties and ease of availability.

2.2.4 Reflective Material

To reflect solar radiations incident on collector dish, a reflective material must be used and applied all across the concentrator surface. The material must have high reflectivity to reflect as much rays incident upon dish as possible, high weathering resistance since the dish has to be placed outdoors, low weight and should be cheap.

Table 2.5 Comparison of different Reflective materials

Sr. No	Material	Weight	Reflectivity (%)	Weathering Resistance	Cost
1	Mirror, silver coating	Moderate	>95	High	Moderate
2	Silver Mylar	Low	98	Very low	High
3	Aluminum Foil	Low	85	Low	Low
4	Foylon	Low	85	Low	High
5	Metal Sheets	High	>80	High	High

Mirror is selected due to it being advantageous for the project in terms of high reflectivity, longer lifespan for outdoor installation and local availability.

3 Methodology

For ease of understanding, the project methodology is summarized in the following flow diagram.

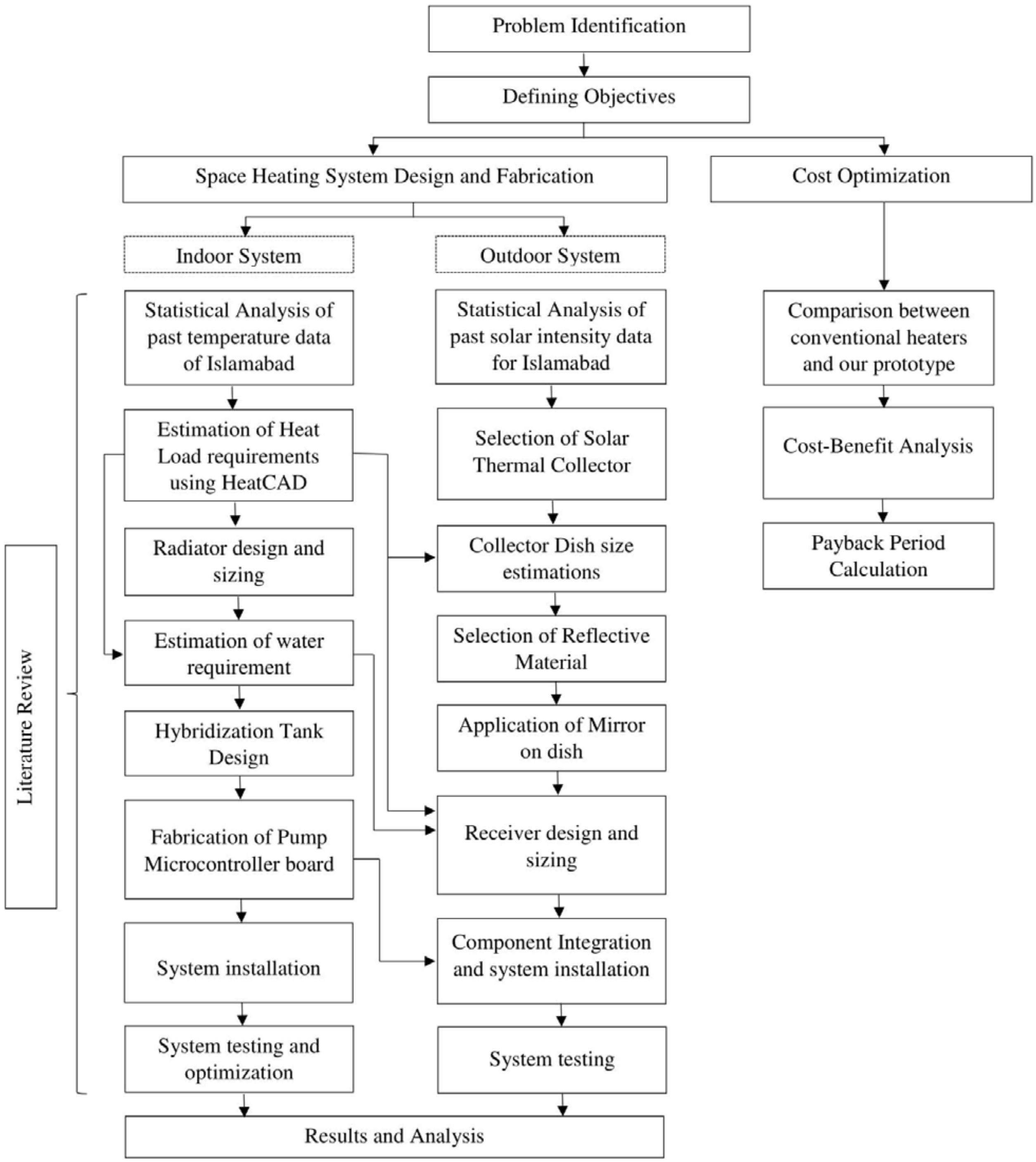

Figure 3.1 Framework of methodology

3.1 Design and Fabrication of Hybrid Space Heating System

The proposed design of space heating system is divided into two units: outdoor and indoor units comprising of various components. The outdoor units includes the outdoor installed assembly solar collector dish along with the receiver. This is solely used for capturing the primary fuel i.e. solar thermal energy. The indoor mounted components include the radiator and the hybridization tank. The hybridization tank serves the purpose of water heating from secondary fuel i.e. electricity. It may be mounted inside or outside but due to ease of use and accessibility, it is decided to be kept inside. Radiator functions to heat spaces making use of water heated from either of the fuels. Control systems are installed all through for component integration and for process control and automation.

3.1.1 Indoor System

The indoor assembly comprises of a radiator and the hybridization tank. A radiator functions as a heat exchanger between working fluid and air. The heat is transferred through natural convection and radiation inside the room. The hybridization tank is a water storage utility that is heated through electricity in times of low solar energy availability.

3.1.1.1 Statistical Analysis of past temperature data of Islamabad

To get an estimate of difference between temperatures to-be-maintained indoors in thermal comfort range and ambient temperature, the temperature data from year 2005-2013 for Islamabad, Pakistan was obtained. The data for winter months i.e. from November to February for the given years was statistically analyzed to determine diurnal and monthly temperature variations and trends.

3.1.1.2 Estimation of Heat Load Requirements

After the ambient temperature data was analyzed, the next phase involved utilization of the data obtained to get an estimation of total heat required to heat the room up to desired limits. For the approximation, a software HeatCAD was used. It is a drawing based software used for estimation of a building's heating and cooling loads following ASHRAE standards. The factors that affect room heat loss include ventilation, construction material, type and size of the room, no. of occupants, heating source etc. The room selected for calculation is present on ground floor, IESE occupying a volume of 1200ft^3 equivalent to 33.98m^3. The room is exposed to outside from one side only. The room consists of one wooden frame door with glass center, one window measuring 23ft^2 made up of glass with metallic frame and internally shaded with blinds (Medium: protection 50%). There is a skylight having area of 16ft^2 having similar construction similar to that of windows. The material used in walls, floor and roof construction is concrete bricks without any insulation. The ventilation doesn't involve forced air ducts, so it is expected to be occurring through windows and door. The air changes in room thus equal 1.14ACH. The no. of occupants is considered to be 3. The plan and 3D views of the room are shown here.

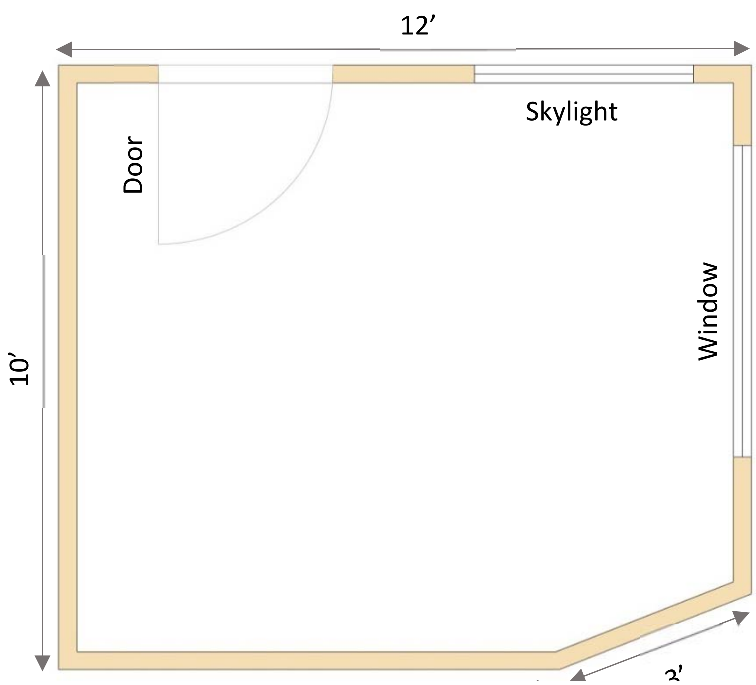

Figure 3.3 Plan view of room for heat load estimations

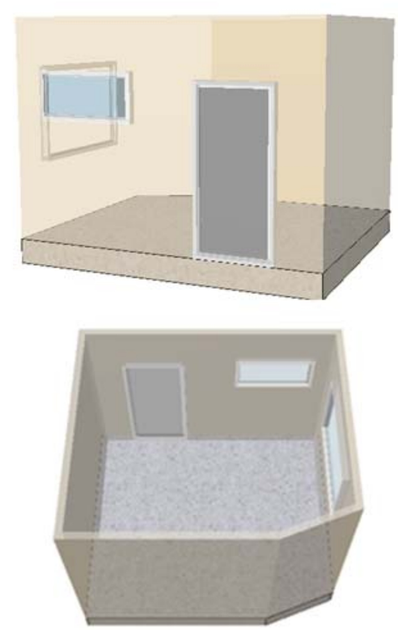
Figure 3.2 3D views of room for heat load estimations

3.1.1.3 Radiator

3.1.1.3.1 Working Principle

A radiator functions as a heat exchanger transferring heat from the working fluid to air. The radiators are preferred for space heating since a long time because of its efficient heat transfer, automated mode of working, ability to make use of natural convection phenomenon and low indoor air emissions.

The radiators employ two fluids: one heat transfer fluid and the other air separated through heat transmission material. Conventionally, the space heaters include a set of tubes and plates and fins making it work as a combination of tube and plate type heat exchanger. The material used for construction is a highly heat conductive material, generally a metal or alloy. The heated fluid is made to pass through the tubes where it transfers heat to the tube through conduction. The tubes are attached to the plates and fins which also get heated up following the same phenomena. The cold, dense air present in the room comes in contact with the heated media of the radiator. At the cold air and heated media interface, heat transfer occurs through radiations generated by the heated media. This air therefore gets warmed up and becomes buoyant and rises up. This is the principle of natural convection followed by radiators to heat spaces *(Bejan A., 2013).*

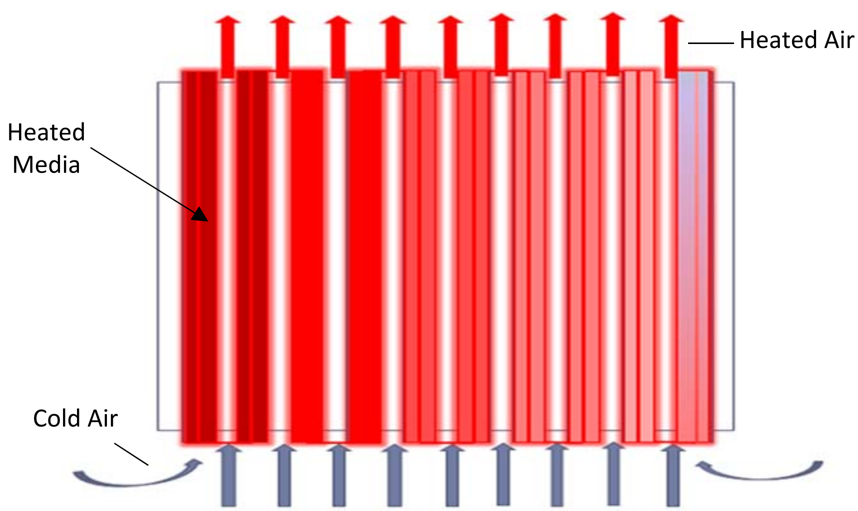

Figure 3.4 Natural Convection phenomena followed by radiators for heating

3.1.1.3.2 Radiator Design and sizing

The proposed radiator design was finalized after study of conventional radiators present in market. To cater for the given heat requirement, the traditional radiators found in market (*Vendor: HeatCON Systems, Islamabad*) are fabricated as tubes of 2mm thickness and 38.1mm diameter attached to plates of 350mm*80mm with same thickness as that of tubes. A total of 10 panels are to be placed parallel to one another to supply the required heat. The total surface area of the assembled unit is 0.65m^2 or 7ft^2.

Our design of radiator included an array of panels placed parallel to one another. Each panel comprised of a metallic plate to which tubes are welded. Copper was selected as material for radiator construction after comparison between different metals and alloys was made. The front view of a single panel is illustrated here:

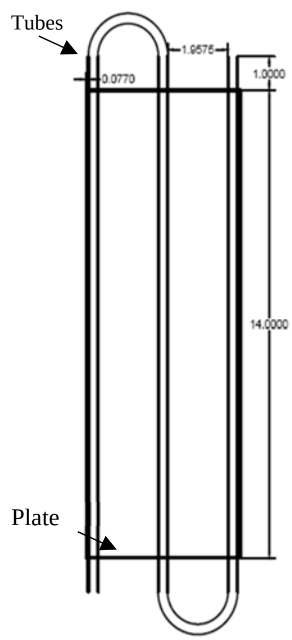

Figure 3.5 Panel front view drawn using AutoCAD

22SWG copper tubes (equivalent to 0.7mm) having a diameter of 8mm were used. The individual plates were sized as 35.6 cm by 15.2 cm with same thickness as that of tubes. The tubes were welded to the plates vertically at one side and were bent at alternate tops and bottoms for regulated water flow. The distance between adjacent tubes on one plate was kept 2.5cm and so 3 tube lengths were present on one plate. Each set of tubes and plate combined formed a panel.

The distance between adjacent panels was kept 2.5cm to allow contact of larger mass of cold air with the radiator. Total fixed volume of tubes was 0.63L and total surface area provided by the radiator was 0.28m^2 or 3ft^2. The dimensions and other specifications are tabulated here:

Table 3.1 Radiator Dimensions and Specifications

Sr. No	Component	Value
1	No. of Panels	11
2	No. of tubes per Plate	3
3	Plate Gauge and Thickness	22 SWG – 0.7mm
4	Plate Length	14" – 35.6cm
5	Plate Width	6" – 15.2 cm
6	Tube Gauge and Thickness	22SWG – 0.7mm
7	Tube Length	18" – 45.7cm
8	Tube Diameter	0.31" – 7.9mm
9	Distance between adjacent panels	2.5" – 2.5cm
10	Distance between adjacent tubes	2.5" – 5.1mm
11	Total Area Occupied	0.75ft2 – 0.07m2
12	Total Surface Area	3ft2 – 0.28m2

From the given plate dimensions and tubular volume, the heat provided by a single panel was calculated to be around 40Watts. Since the total heat requirement was estimated to be 400Watts, a total of 11 panels constituted one single radiator unit, an additional panel to cater for unanticipated loads.

Figure 3.6 Our manufactured Radiator

3.1.1.4 Calculation of Required Water flowrate

Since water is the primary source of heat supply to radiator media and air, it is important to accurately determine the flowrate of water needed and to what temperature it should be elevated to bear the requirements. The fixed volume of the tubes of the radiator is 0.63L but since water has to flow through the loops (hybridization tank-radiator, receiver-radiator), additional water must be present. Hence for the given loop lengths, a minimum of 7L of water must had to be present at all time to ensure accuracy of the system. To make a trade-off between initial heating time and energy optimization, the temperature to which water is heated was set as 72.5^{o}C. The flowrate of the water was kept 6.67L/min instead of 3-3.5L/min in traditional radiators, to enhance heat transfer rate from water to air while optimizing heat transfer time with energy saving.

3.1.1.5 Hybridization Tank Design

During times of low sunlight availability, such as early morning, night time or during overcast, the water present in the hybridization tank was heated by electric rod and made to flow through the radiator. The tank was placed inside the room for convenience in use. For testing purposes, we recycled an edible oil container and renovated it into a fully functional hybridization tank. The capacity of the tank was kept 3L. Initially, the water heating was done using DC-operated rod but was found unsuitable as the initial heating time became very long. The heating element then selected for water heating was a 700Watt, AC-run electric rod. The rod was immersed inside the tank supported by a wooden lid that was fixed at the tank opening. The lid served the dual purpose of minimizing heat escape from the tank. To make the tank energy conserving, the rod was thermostatically controlled with a set point of 72.5°C. Although not observed in our case, the AC operated rod carries certain risks like electrocution or flash burns etc. with it but it can be diminished by proper insulation of the tank. Since it was only used for testing purposes, if commercialized the inside of the tank must be lined with an anti-corrosive agent to disallow corrosion and subsequent water quality degradation that may cause fouling. Also, if the tank is to be kept at a place where it does not indirectly contribute in room heating, it must be thermally insulated to lessen energy losses.

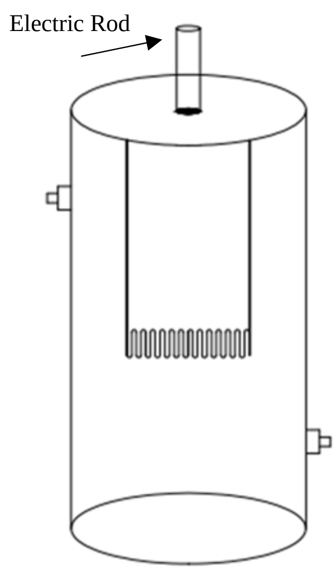

Figure 3.8 Front view of initial design of hybridization tank

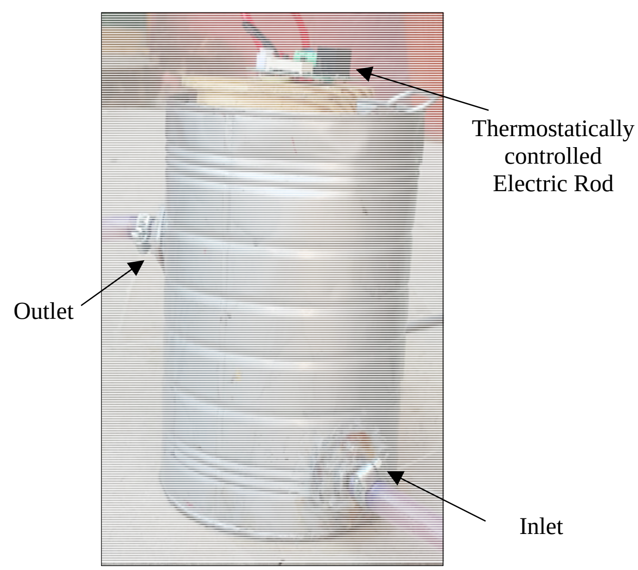

Figure 3.7 Our fabricated hybridization tank assembly

3.1.1.6 Control and Programing of Pump

To make water flow from heating source to radiator and vice versa, a pump was used. The selected pump type was a non-submersible, centrifugal water pump. It was DC-operated with a rating of 12 V – 8Watts. The pump was chosen due to its ability to maintain the projected flowrate i.e. 6.67L/min, very low power utilization and safety purposes. The maximum head to which it could deliver water was 5m which also fulfilled our needs. The pump was controlled through a microcontroller integrated with Arduino for multiple purposes: first one was to make it energy conserving, secondly to control water flow through the radiator and for lengthening the lifespan of pump reducing maintenance costs. The microcontroller used to give the pump a rest of 30 seconds after each 90 seconds of working. Since it was DC operated, an adapter (Rating: 12V, 18A) was used to make it compatible with on-grid electric supply.

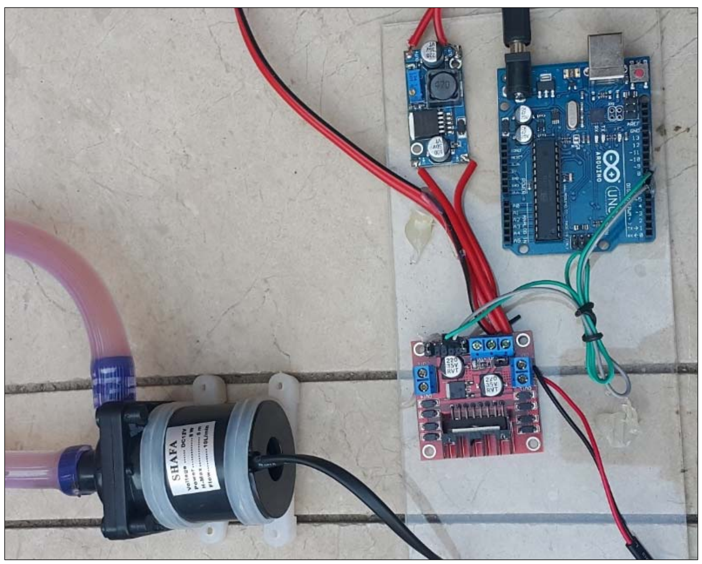

Figure 3.9 Fabricated pump microcontroller board

3.1.1.7 System Installation

After all the indoor components were fabricated and set-up, the system was installed inside the room for which the heat requirements were initially anticipated. The arrangements were made so as to allow maximum contact of cold air with radiator. High quality rubber pipes were used to connect radiator and hybridization tank for water passage in between. The pump was set between hybridization tank outlet and radiator inlet to allow hot water flow. Valves were used to control the flowrate of water into the radiator.

3.1.1.8 System Testing and Optimization

Testing was performed to evaluate the validity of design. Inlet water temperature was made variable and adjusted against initial heating time and energy optimization until an optimal value was achieved. The experimentation phase involved measurements of ambient temperature and the temperatures maintained indoors. A local weather station located in F-11 Markaz, Islamabad provided ambient temperature record during days on which testing phase was conducted. The indoor temperature was measured using a data logger shield that sensed and recorded indoor temperature data with precision up to one decimal place, and at interval of a second. The water temperature at radiator outlet was also recorded using a lab-scale thermometer. Time required to initially observe temperature change by a margin in room and then for each degree rise till desired was maintained, were also measured. The data obtained was later analyzed. The testing equipment used is shown here:

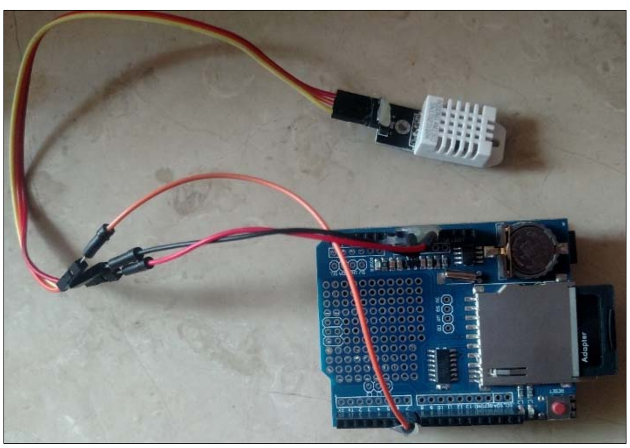

Figure 3.10 Data Logger Shield for indoor temperature measurement

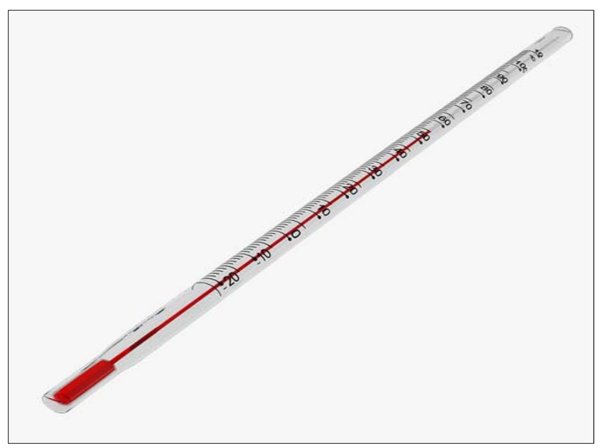

Figure 3.11 Lab-scale thermometer for water temperature measurement

3.1.2 Outdoor System

The outdoor system consists of solar collector dish and the receiver. Solar collector dish is a parabolic dish having a diameter of 6ft with mirror applied on it as reflective material. It is used to capture the incident solar rays and reflect them onto a point where receiver is mounted. The reflected rays heat the working fluid present in the receiver that is then made to flow through the radiator.

3.1.2.1 Statistical Analysis of past Solar Radiation Intensity data of Islamabad

The primary fuel for the system is solar energy, therefore it is necessary to assess and check whether adequate solar radiation is present over the day to fulfill the requirements or not. The diurnal variations of Islamabad for winter months i.e. November to February were statistically evaluated for the years 2015-2017 due to restricted data availability. The average solar radiation intensity variations for all the 4 winter months are plotted against daytime hours i.e. from 9a.m. to 5p.m.

3.1.2.2 Selection of Solar Thermal Collector

The purpose of solar collector is to capture the incident solar rays and utilize them or store them as heat energy. There are many types and configurations available in market today to serve the purpose. Solar collectors may either be concentrating or non-concentrating. In the non-concentrating type, the collector area (i.e. the area that intercepts the solar radiation) is the same as the absorber area (i.e. the area absorbing the radiation). Concentrating collectors have a larger interceptor or receiver than their absorber; common types include parabolic troughs and parabolic dishes. Since the water is to be heated up to temperature of 75-80^{o}C, the concentrating type collectors are preferred. Out of these solar parabolic dish collector is preferred because of its increased efficiency and insignificant convective and end losses due to small absorber area. Also it provides ease of fabrication at lowered costs. The shape of a parabolic dish is so as to reflect the incoming light rays incident parallel to the dish's axis towards the focal point, no matter where on the dish they arrive. Since solar rays fall parallel on earth surface, the dish is adjusted with its axis pointing directly towards the sun allowing as much capture and reflection of the rays as possible. One problem associated with use of parabolic dishes is having a smaller angle of view, for which manual or automatic solar tracking is required.

3.1.2.3 Collector Dish Sizing

After the collector type was selected and heat requirements for the room were estimated, the dish was sized to satisfy the given requirements. A pre-fabricated parabolic dish was used later made into a solar parabolic dish concentrator. To get an estimate of power that can be intercepted from the dish, the following calculations were made:

Aperture Area of Parabolic Dish

$$A_{aperture} = \frac{\pi}{4} * D^2 \qquad (1)$$

Where

A = aperture area

D = diameter of the dish

$$A_{aperture} = \frac{\pi}{4} * 6^2$$
$$A_{aperture} = 28.27ft^2$$
$$A_{aperture} = 2.63m^2$$

Focal Length of Parabolic Dish

$$F = \frac{D^2}{16*h} \qquad (2)$$

Where

F = focal length of the dish

D= diameter of the dish

h = depth of parabolic dish

$$F = \frac{6^2}{16 * 0.8}$$
$$F = 1.8\,ft$$
$$F = 0.55m$$

Heat Received from the Collector

$$Q_{received} = A_{aperture} * I * \rho \qquad (3)$$

Where

$Q_{received}$ = *rate of heat received from the given concentrator (kWh/day)*

$A_{aperture}$ = aperture area of the parabolic dish (m^2)

I = Solar irradiance ($kWh/m^2/day$)

Value taken as an average of 4.25$kWh/m^2/day$ during winter season for Islamabad

ρ = reflectivity of reflective material on the dish (%)

Value taken as 95% for mirror

$$Q_{received} = 2.63 * 4.25 * 0.95$$

$$Q_{received} = 10.62\ \frac{kWh}{day}$$

If the day length is 8 hours,

$$P_{received} = 10.62 * 8$$

$$P_{received} = 84.95\frac{kW}{day}$$

Where

P = power received (Watts)

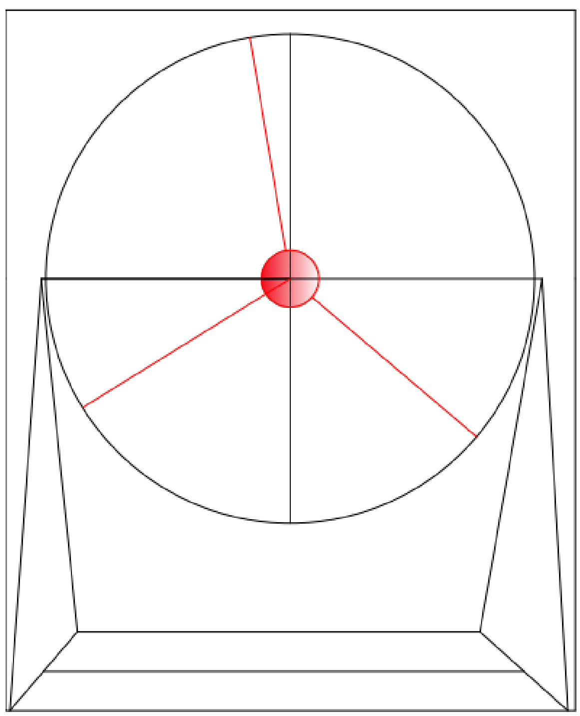

Figure 3.12 Front view of AutoCAD drawn Solar Collector Dish

The solar dish assembly is placed on a movable stand to allow easy adjustment of dish on dual axes.

3.1.2.4 Reflective Material

Mirror was chosen as reflective material after thorough research and comparison between different materials was conducted. 2mm thick glass mirror was used and glued to the curved side of the dish as squares of 1.5 inch by 1.5 inch using high temperature resistant and water proof adhesives. A total of 1800 pieces were hand-pasted on the dish. The mirror provided high reflectivity and high weathering resistance at low cost and ease of availability. Also, the weight of the dish was adjusted by the weight of mirror to withstand harsh weather conditions. The collector dish onto which mirror had been applied and receiver had been mounted, installed on IESE rooftop is displayed here:

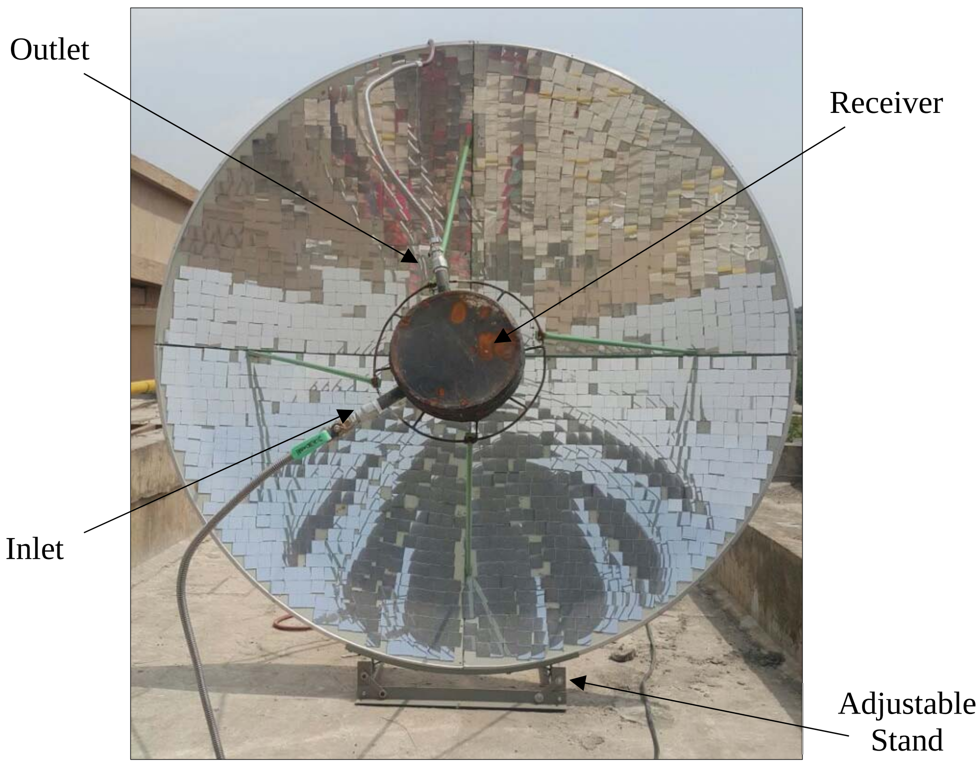

Figure 3.13 Integrated Solar dish and Receiver assembly installed at IESE rooftop

3.1.2.5 Receiver Design

The receiver is the component placed on focal point of concentrating solar thermal collectors that receives concentrated and reflected radiations heating up the working fluid present in it.

Generally, it is made up of a highly conductive material to maximize the heat input to the working fluid. Many shapes and configurations of receiver exist depending upon collector type. Receiver shape, size and the material by which it is made all have a major effect on working as well as efficiency of solar dish. The material hence chosen for receiver construction of this project was stainless steel. It was chosen due to its large thermal conductivity, high corrosion resistant as it has to be placed outdoors and low cost. 2mm thick steel sheet was morphed into a disk shape having a diameter of 1.5 feet and base height of 2.5 inches. The total capacity of the receiver was thus, 4L although the water was filled up to a level of 3.5L only. The water inlet was present at the side of the receiver while outlet was at the top. The receiver was painted black using spray paint to further enhance its absorptivity. The receiver was mounted to the concentrator using 4 iron rods fixing it exactly at dish's focal point and pre-calculated focal length. Originally, the design included thermal insulation of the receiver from all sides excluding the one directed onto curved side of the dish but due to cost and time constraints it was exempted. The heat losses from the receiver were still found negligible as for the scope of the project.

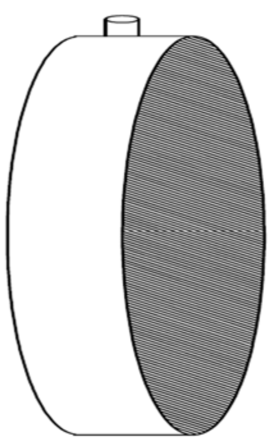

Figure 3.15 Side View of Receiver drawn using AutoCAD

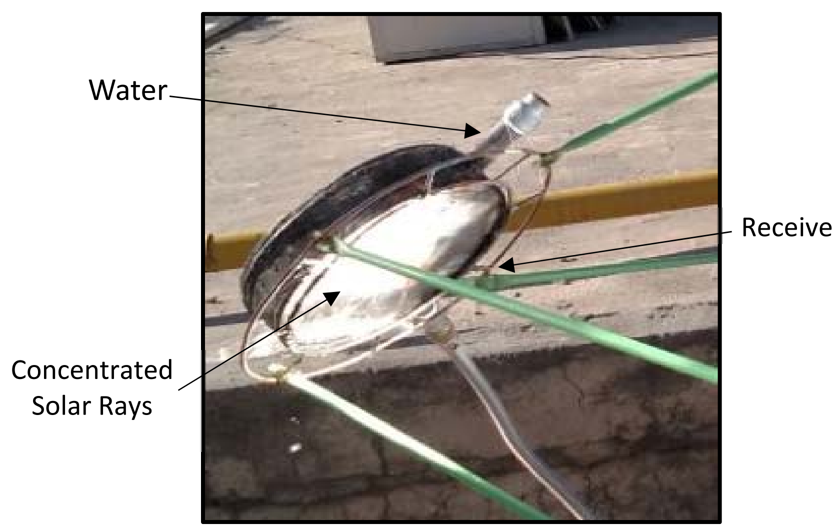

Figure 3.14 Mounted receiver with dish

3.1.2.6 Component Integration and System Installation

After their fabrication, the dish and receiver were integrated together and the assembly was installed at rooftop of IESE, NUST. The dish was supported on an adjustable iron stand through which the angle of the dish facing sun could be adjusted multi-axially. The receiver was fixed at focal point of the dish at pre-calculated focal length of the dish by the support of iron rods. The assembly was placed directly above the room in which testing was to be conducted to shorten the loop length. From receiver to a fixed length, stainless steel pipes were used for water conveyance. The use of stainless steel pipes was done because high temperature water could cause degradation of rubber pipes in less time. The pump was used to convey working fluid i.e. water to and fro receiver-radiator. Possible thermal energy losses from pipes could be reduced by proper insulation.

3.1.2.7 Experimentation

Due to time constrictions, the outdoor system was tested autonomously. The dish's angle was manually adjusted so as for the reflective side of the dish to face the sun directly. During month of April, 2018 the testing was conducted. It involved measurement of initial water temperature in receiver and the time required to elevate the temperature up till 80^{o}C on hourly basis. The pump was stopped when water temperature rose beyond 80^{o}C as at higher temperatures phase change of water could occur for which our system was not designed. The water temperature was recorded using lab-scale thermometer by immersing it in receiver outlet's valve opening. The solar intensity data for IESE, NUST was provided by weather station installed at the same place as that of our outdoor system. The data obtained was then analyzed.

4 Results and Analysis

The testing methodology involved two phases: First one involved testing of indoor system to check for radiator's efficiency involving water heating through electric heating element. The second phase was water heating through outdoor solar-capturing assembly to determine its efficiency independently. Both the systems were first optimized and then checked for their suitability and proficiency as either stand-alone system or as integrated unit.

4.1 Statistical Analysis of past Temperature Data of winters for Islamabad

The average temperature variations over the day from 9 a.m. to 9 p.m. from November to February for years 2005-2013 are graphically represented here. The selected time frame is chosen because the project targets audience in residential and institutional buildings.

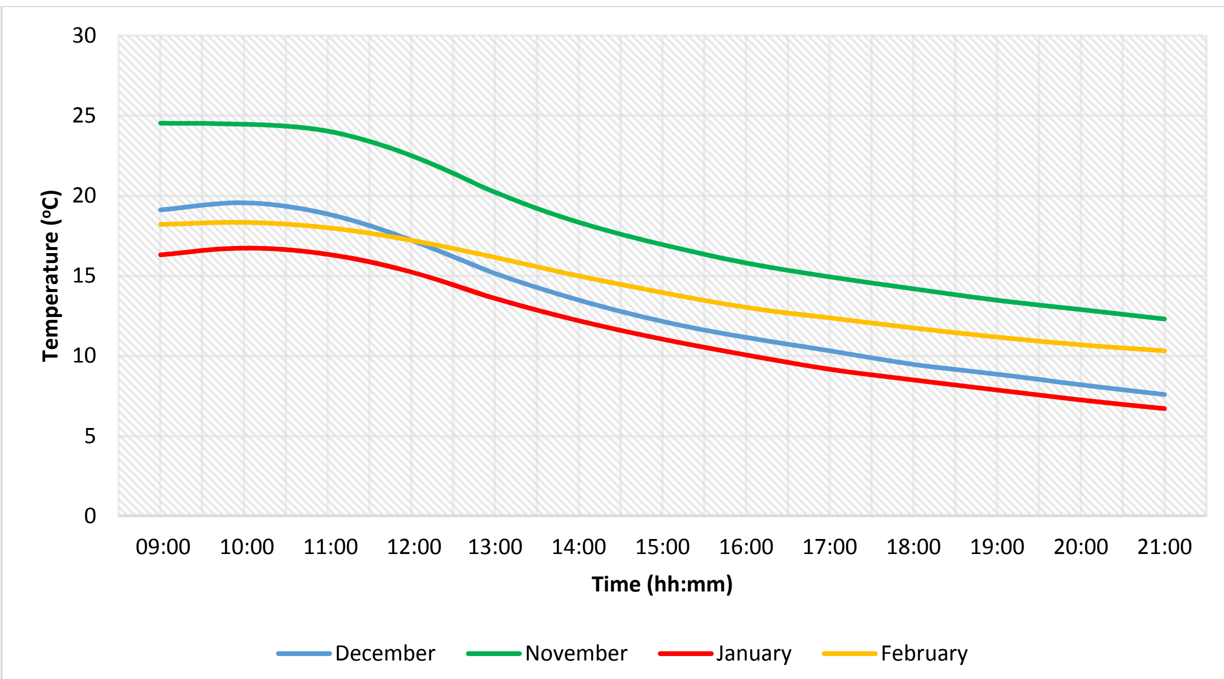

Figure 4.1 Statistical Analysis of Temperature variations during winters from 2005-2014 in Islamabad

It can be inferred from the graph that average lowest temperatures over the day were recorded for January for the given years. The average temperature for November was assessed to be 16.57°C, for December the value remained about 11.53°C, for January it fell down to 10.00°C and in February it remained about 13.05^{o}C. The average value for these four months combined was found to be 12.78^{o}C.

The temperature during winters from 2005-2013 reached a maximum of 30^{o}C, a minimum of -2^{o}C and most commonly occurring temperature was determined to be 11^{o}C. However, the system design was based on average data values.

4.2 Heat Load Estimations

Through the before mentioned input, the heat load requirement estimated from the software came out to be 400Watts for temperatures to be elevated from 12.78^{o}C to 23.5^{o}C (lies in thermal comfort range of ASHRAE standards). The component wise load breakdown of this value is represented below. This value was utilized for design of radiator as well as both of the fuel-utilizing components. This value matches with the original heat requirement of the room found during experimentation phase.

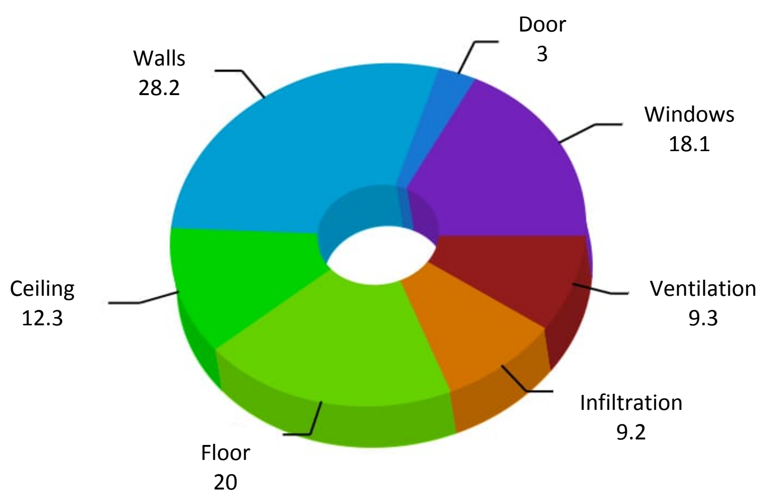

Figure 4.2 Component breakdown of estimated heat load as % of total heat requirement

4.3 Statistical Analysis of past Temperature Data of winters for Islamabad

The average solar radiation intensity variations over the day from 9 a.m. to 5 p.m. from November to February for years 2015-2017 are graphically represented here.

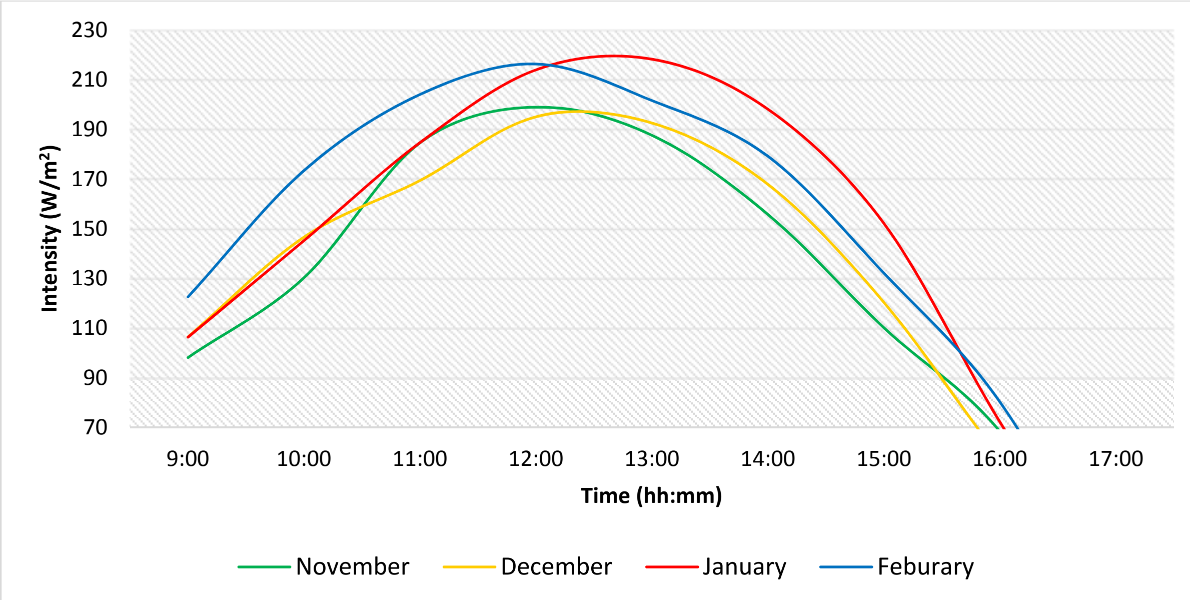

Figure 4.3 Statistical Analysis of Solar radiation intensity variations during winters for years 2015-2017 for Islamabad

The graph depicts that lowest solar intensity was found in month of November over the given years. The day length was found to be shortest in December as expected. Average intensity remained about 141.76W/m^2, 144.52 W/m^2, 161.37 W/m^2 and 163.70 W/m^2 for November, December, January and February respectively. Over through the four months, the average intensity from 9a.m. to 5p.m. was found to be 152.84 W/m^2.

4.4 Phase 1: Water heating using Electrical energy

The first phase involved use of hybridization tank to run the radiator. The assembly was adequately placed so as to allow maximum interaction between radiator and cold air inside the room for which heat requirements were calculated earlier and in which experimentation was being performed. The electric rod dipped inside the hybridization tank had electrical input of 700 Watts and was AC-operated. The rod was first gone through security check to minimize the chance of any hazard that may occur later in time. Since the modern electric heating elements are designed and insulated to avoid current passage through water, the assembly is stated safe enough to be used indoors and is user friendly too. The system was initiated daily at 9:00a.m by switching on the rod. The water was given sufficient time to warm up to a reasonable temperature after which the pump was turned on and water started to flow through the radiator tubes. The time taken by water temperature to rise by a degree was recorded. At first place, the temperatures inside the room were recorded using data logger shield that sensed temperatures in degree Celsius with a precision of one decimal place and at interval of each second. The time required by the system to initially observe difference in room temperature and then subsequent increase by each degree till desired temperatures were achieved were recorded, too. The values obtained were compared and related to ambient temperatures obtained from database of a weather station located at F-11 Markaz, Islamabad. The testing was performed for a span of 1.5 months and the values obtained were averaged. The ambient as well as indoor maintained temperatures are plotted next to each other against time for comparison.

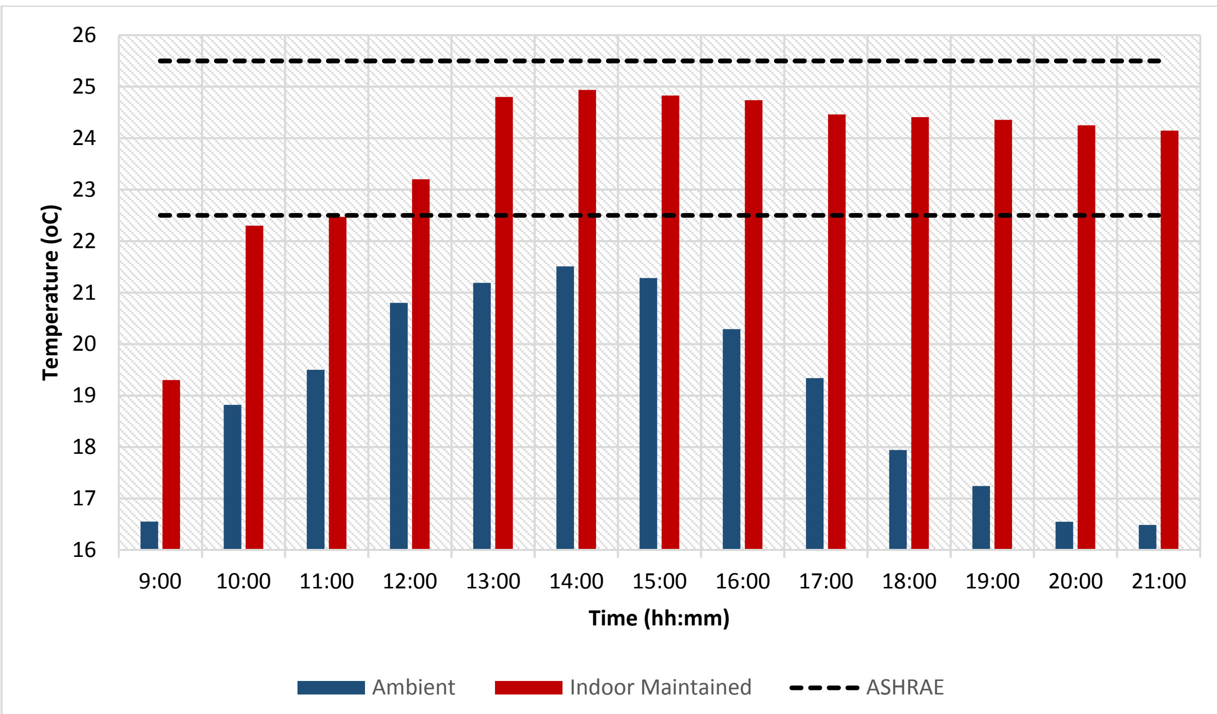

Figure 4.4 Ambient and Indoor maintained temperatures plotted versus time

The average ambient temperature for the day remained about 16.6°C. The average temperatures varied between a minimum of 16.5°C and a maximum value of 21.3°C. The minimum and maximum temperature recorded during experimentation span were recorded as 12°C and 24.6°C, respectively. The initial temperature of the room was observed to be 2-3 degrees higher than the ambient with an average value of 19.3°C.

When the radiator was run, the room's temperature increased promptly. For initial rise in temperature by a degree, the average time taken was 25 minutes, far less than that of conventional radiators that take minimum 50 minutes to initiate room heating. When the ambient temperatures fell drastically low, the time taken was observed to be 30-35 minutes. Following the initial heating time, each degree rise afterwards took an average of 41 minutes. The increase in heating time is attributed to shrinking of temperature gradient between ambient and indoor.

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation *(ANSI/ASHRAE Standard 55).* Since HVAC industry in Pakistan widely follows ASHRAE Standards, it was intended to make the system efficient enough to maintain the temperatures indoor in their thermal comfort range that lies between 22.5^{o}C to 25.5^{o}C. It was observed that at most time of the day, the ambient temperature was below the defined range. The system proved efficient in maintaining the temperature in thermal comfort range at most time of the day excluding the preliminary hours of system initiation, as can be inferred from the graph.

The temperature data was also analyzed in terms of heat available and transfer from one medium to other. By measuring the time taken by water to get heated up to desired temperature, the power intercepted by the water from electric rod was calculated according to the following equation:

$$Q = \mathrm{m} * c * \Delta T \qquad (4)$$

Where

Q = Heat intercepted (J)

ṁ = mass of water (kg)

c= specific heat capacity of water (J/kg. C)

ΔT = temperature difference (^{o}C)

If the difference in water temperature is, on average, 55.9^{o}C, the power intercepted by the water inside hybridization tank is

$$Q = 3 * 4200 * 55.9$$

$$Q = 704.34 \text{ kJ}$$

Since initial water heating time is on average 35 minutes, the power intercepted by the water is

$$P = \frac{704.34 * 1000}{35 * 60}$$

$$P = 335.40\text{Watts}$$

This is the power available in water that can be delivered to the radiator media and then air. Since the electrical input of the rod is 700Watts, it is therefore calculated that thermal efficiency of the rod is 48%.

For measurement of power required to elevate the temperature of the room by a degree, water temperature drop while flowing through the radiator tubes was measured. At the radiator outlet, the thermometer was immersed in the valve opening to measure water temperature after one cycle of the pumped water was completed. It was then compared with the inlet water temperatures i.e. 72.5°C. The results showed that water dropped a minimal amount of 0.5-1 degree while flowing through the radiator tubes and heating up its media. Since copper is highly thermal conductive and specific heat capacity of air is very low, this value proved reasonable for efficient rate of convective heat transfer from water to air. This difference was then incorporated to evaluate the power needed to elevate the temperature using the same equation.

$$P = \dot{m} * c * \Delta T \qquad (5)$$

Where

P = Power intercepted (Watts)

ṁ = mass flowrate (kgs/sec)

c= specific heat capacity of water (J/kg. C)

ΔT = temperature difference (°C)

$$P = 0.11 * 4200 * 0.5$$

$$P = 233.45\text{Watts}$$

This is the minimum power required to increase the temperature of the room by a degree using the given system and for room size and conditions.

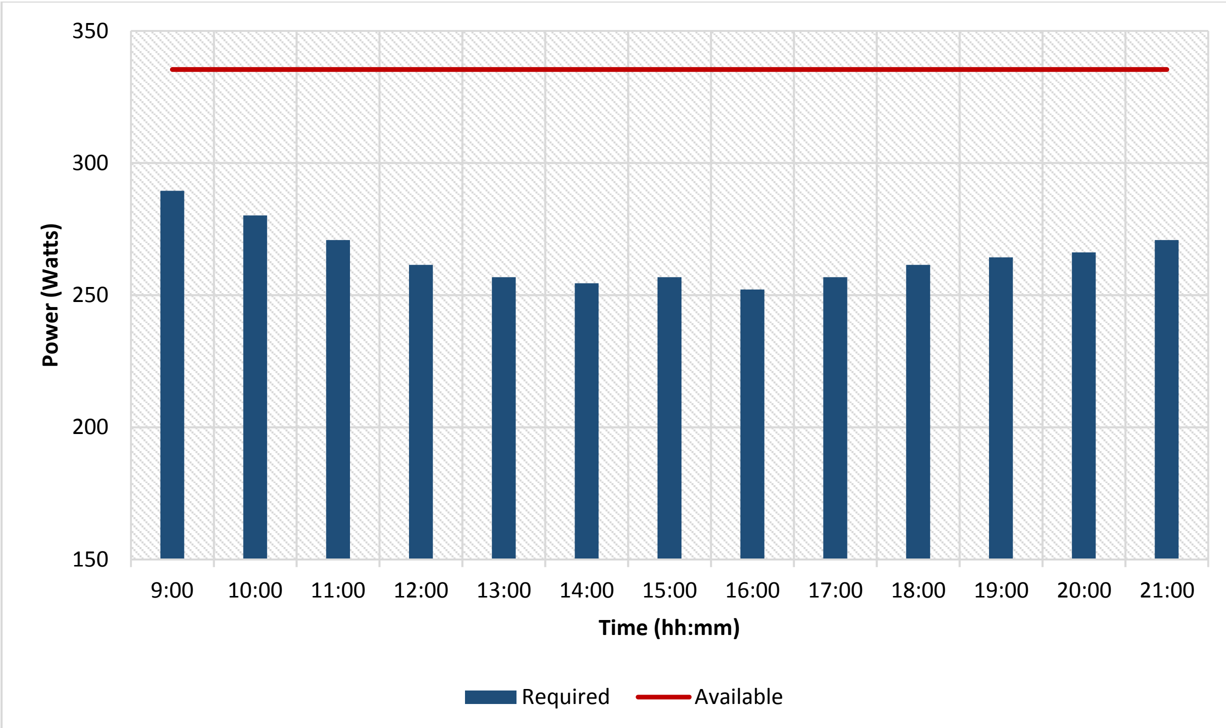

Figure 4.5 Power Available vs Power required per unit time for hybridization tank

From the graph, it can be inferred that during times when the ambient temperature is low, the system intercepts a large amount of power from the water due to large temperature gradient. The power requirement at each hour are below the power available in water proving the sufficiency of electric heating element and the hybridization tank. This analysis also satisfies our initial radiator design estimations as the unit has been proficient in terms of required heat deliverance.

4.5 Phase 2: Water heating using Solar Energy

During the second experimentation phase, the outdoor system was tested. Solar Radiation Intensity, increment in water temperature inside receiver and the associated time were recorded.

Firstly, to estimate outdoor system's efficiency, the power available from solar energy and intercepted by both collector dish and receiver were measured. In the month of April 2018, the testing was performed during daytime hours. Water in the receiver was filled up to a fixed level and dish was positioned according to sun's direction. Using thermometer, water temperature was gauged at an interval of 5 minutes. When the water temperature touched 80°C, the pump was switched off. The experiment was repeated every hour of the day to check for difference in heating time due to variable intensity associated with varying solar angle during daytime. The difference in water temperature helped in calculation of power intercepted by working fluid in receiver.

The average solar radiation recorded during the daytime was 363W/m^2. Since the collector areas is 2.32m^2, the average power available to the receiver was 950Watts. The power intercepted by water in receiver is calculated from equation (4).

$$Q = 3 * 4200 * 60$$

$$Q = 756\text{kJ}$$

The average heating time was measured to be 17.5 minutes, the power intercepted by working fluid is:

$$P = \frac{756 * 1000}{17.5 * 60}$$

$$P = 721\text{Watts}$$

The outdoor system efficiency is thus calculated to be 74.4%. The possible losses are due to convection (heat transfer to surrounding air causing it to become buoyant) taking place around and near receiver and from transmission pipes. End loss may also be attributed to decrease in efficiency. It is a measure of losses occurring due to reflected rays falling beyond the circumference of the receiver. It was observed that maximum reflected rays were concentrated upon the receiver making convective loss predominant heat loss phenomenon here.

Relationship between sunlight availability and intercepted by water is demonstrated here. It is evident from the below represented graph that during peak sunlight hours, the power available per area of concentrator was high and so was the power intercepted by water in receiver making heating time smaller. Maximum radiation intensity of 437W/m^2 was recorded at 12:00pm and a minimum value of 272W/m^2 at 4:00pm with average value calculated about 363W/m^2.

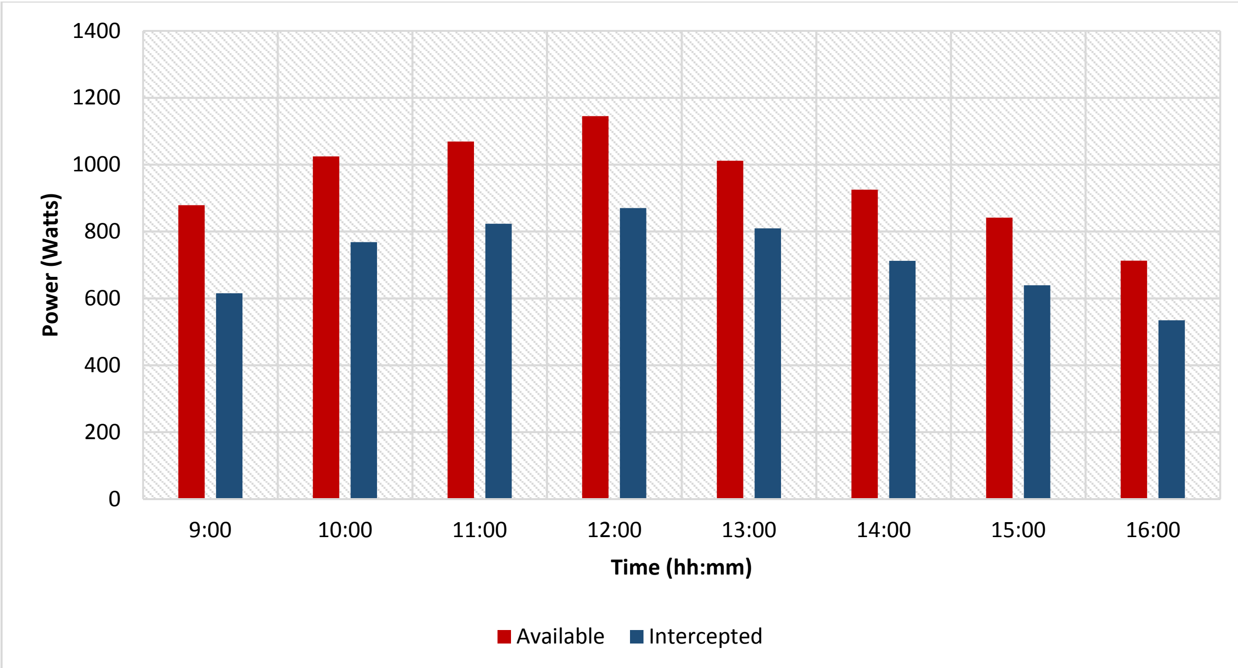

Figure 4.6 Power available and intercepted to/by outdoor system during daytime hours

4.6 Analysis

As the testing of outdoor system was done in a non-winter month, it was necessary to assess whether the system is able to work in winter conditions. For this, the previously analyzed solar radiation data of Islamabad was evaluated for the power it can deliver against the average power required to maintain room's temperature in preferred range.

The solar radiation intensity in winter is averaged as 156.07W/m^2 which means that the radiation incident upon the dish is on average 411Watts, since the receiver is capable of receiving 75% of this power, the power water can intercept from solar energy during winters is around 310Watts. The average power required in maintaining room temperature is 260Watts, the efficiency of the outdoor system is therefore, proved. Even if we take in account the transmission losses, the power available exceeds the power required (Figure 4.4).

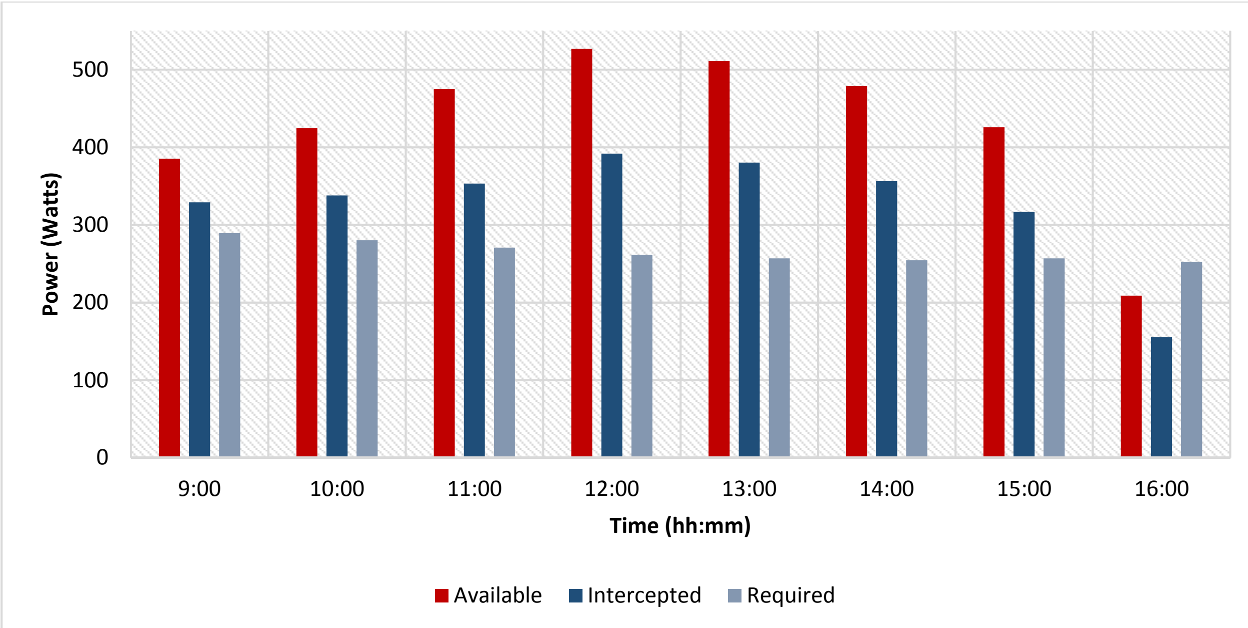

Figure 4.7 Comparison between Power available, intercepted and required plotted vs daytime hours

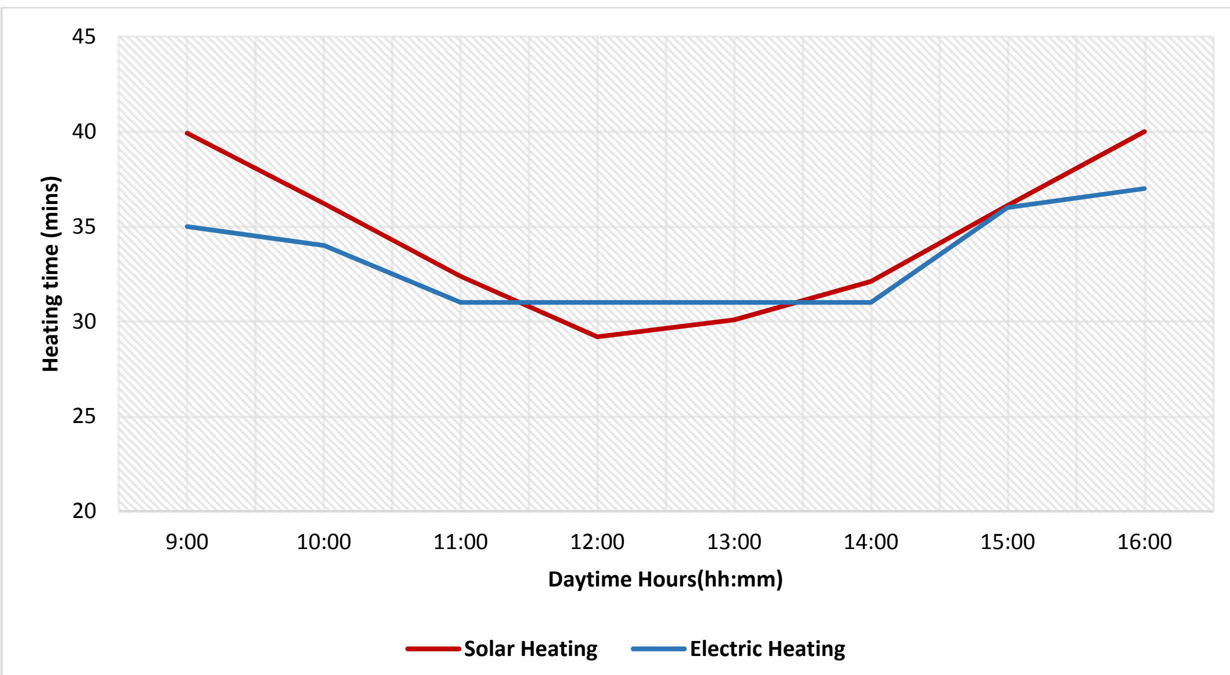

Figure 4.8 Initial water heating time comparison between solar and electrical heating

The graph above shows initial water heating time during daytime hours, if assumed at each hour the water temperature is comparable to the ambient temperature. Measured temperature is the one measured during testing phase involving solar heating. An average of 16.5 minutes were taken by given volume of water to reach up to 80^{o}C. The analyzed heating time is done by comparing analyzed intensities to that of measured. It gives an estimated average heating time of 33.7 minutes. The time taken by electric heating element is also shown in graph with an average of 35 minutes. Hence it is concluded that the time taken by either of the heating component is comparable.

So, through the analysis it is evident that solar energy is amply available from 9a.m. to 4p.m. during winters and the outdoor system is capable of capturing it with enough efficiency to deliver room's heat load. For rest of the time of the day, if the radiator is to be used, the hybridization tank can be used which alone has proven to be sufficient for the requirement and with nominal power input.

5 Cost Analysis

5.1 Comparison between conventional radiator heating system and our prototype

The following table summarizes the benefits our prototype of Radiator and heating system has over conventional radiator and boiler system in market. It is apparent that the conventional boilers are expensive and highly energy intensive, with low conversion efficiency hence making the operational costs very high. Our designed prototype makes optimal use of energy, delivering loads at high efficiency and with negligible costs.

Table 5.1 Cost comparison between conventional radiator heating system and our prototype

Sr. No	Parameter	Conventional Radiator and boiler system	Our Prototype
1	Capital Cost	80,000	20,000
2	Energy input*	2468Watts	411Watts from Sun 700Watts from On-grid Electricity
3	Initial Heating time	50-55 mins	25-30 mins

4	Energy output	300Watts	235Watts
5	Operational Costs**	PKR 256	Zero from solar heating PKR 80 from electrical heating
6	Maintenance Cost (estimated)	15% of capital cost	8% of capital cost
7	Indoor air emissions	Medium – High***	Low

**Based on standard water heater size of 10L used solely for one radiator unit*

***Based on the estimation of running the radiator unit continuously for 8 hours a day, considering per unit cost of electricity as Rs.13*

****High if boiler is run by natural gas*

5.2 Cost-Benefit Analysis

Making use of the above mentioned data, the monetary benefits we get from the system is in its low energy consumption. If the system is solely run on solar energy for 8 hours daily, the operational costs are zero. But if we assume that solar energy availability is in one way or other stalled, the use of hybridized unit also needs optimal energy input and the cost for continuous running for the same time is a mere 80Rs. Based on this, the yearly cost saving is high. Although the system is designed to maintain its sustainability over longer periods of time, it is still considered into account that some of the components may malfunction and need replacement or maintenance once in a while. The components vulnerable to damage include the pump, electric heating element, outdoor dish and miscellaneous. It is roughly estimated that the outdoor system needs periodic cleaning, especially after harsh weather conditions, electric heating element may require changing after 2-3 seasons of continuous working and pump may require replacement after each season of use. This roughly makes the maintenance cost per season, 8% of the capital cost i.e. 1600Rs.

5.3 Payback Period

The graph here graphically portrays the cost-benefit analysis of our project. The capital cost of all of the system was approximately 20,000Rs with the maintenance cost per season of the system calculated as about 8% of the capital cost. The net profit line here shows the profit in terms of electricity cost saving minus the maintenance cost. If, all through the daytime the system runs on solar power, we can save about 8000Rs from electricity cost per season. With an estimated lifetime of about 10 years of the system, total cost saving climbs high. This saving in cost makes the payback period of the system to be around 2.8 seasons or 10 winter months. It is to be emphasized here that the cost being saved in terms of reduced pollutant emissions, lower health risks and environmental preservation are unparalleled.

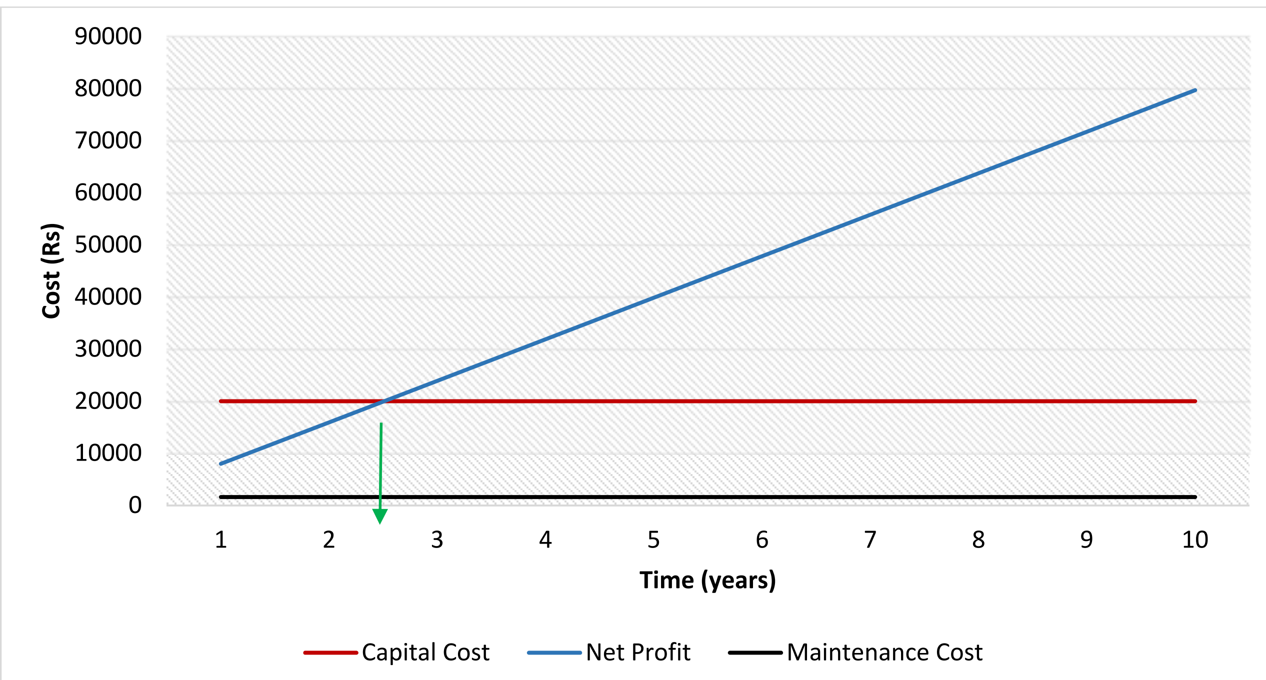

Figure 5.1 Cost-benefit Analysis of our prototype

6 Conclusions

Based on project objectives of designing an energy efficient, low indoor emission space heating system and cost optimization by making optimal use of energy and use of local materials for system's fabrication, the results of our design and research on the product have led us to conclude our project as:

- Solar energy is sufficiently available during winter season to cater for prime energy demands in residential sector and institutional buildings during day time.
- Independent testing of the outdoor system determined its efficiency to be 74.5%. The possible losses observed are end loss and convective losses through receiver.
- The heat output of electric rod was calculated to be 336Watts, calculating its efficiency to be 48%.
- The energy output of the radiator matched with the pre-estimated values proving accuracy of the proposed design.
- The average initial heating time by electric heating rod and solar energy is 35 minutes and 33.7 minutes (estimated), respectively.
- Both of the heating components prove reliable and steadfast as either stand-alone system or as an integrated unit.

- Comparison between traditional radiator and boiler systems and our designed system prove our design's efficacy over them in terms of reduced capital, operational and maintenance costs, as well as low energy input and high rate of converting it to useful output and with minimal indoor and outdoor air pollutant emissions.
- The payback period of the system is calculated to be a mere 10 winter months.

7 Recommendations

Considering the extent of the project and through comprehensive observations during the course of the project, here are some of the recommendations that we think must prove advantageous in further improving overall system efficiency.

- Since the pump is DC-operated, if we install a small Photovoltaic module in our system to run the pump, during solar energy availability, the system would be completely independent of on-grid electricity in day time. It may be noted that energy utilization of the pump still is very low.
- Automated Solar tracking of the outdoor dish in dual axes would make it much efficient and reduce human load of manually adjusting the dish in sun's direction.
- Thermal insulation of receiver and connecting pipes would significantly reduce the heat losses through them making more heat available to the radiator. The insulator selected for our purpose was rock wool, however, better insulation materials with large R-value can be used for enhanced system performance.
- To eliminate risk hazards such as electrocution, flash or thermal burns, associated with use of electric rod, proper insulation of rod as well as the hybridization tank (made up of metal) is

important and must be done. Also, a level sensor maybe installed in it for continuous checking of water level which otherwise would result in short circuiting.

- Thermostatic valves maybe used to control water flowrate into the radiator that can help alter temperature set point inside the room as per residents' will.
- Another potential application of solar thermal energy that can be coupled with space heating system is solar water heating. Hot water is generally required all through the year, the integration of two systems would increase overall working performance of solar dish which would otherwise be only used during winter season. Also, there would be significant increase in cost saving and reduction in indoor air pollutants.

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